AWARD NUMBER: W81XWH-15-1-0417

TITLE: Sensory Feedback for Lower Extremity Prostheses Incorporating Targeted Muscle Reinnervation (TMR)

PRINCIPAL INVESTIGATOR: Eric Rombokas, PhD

CONTRACTING ORGANIZATION: Seattle Institute for Biomedical and Clinical Research
Seattle WA 98108

REPORT DATE: October 2017

TYPE OF REPORT: Annual

PREPARED FOR: U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

DISTRIBUTION STATEMENT: Approved for Public Release;
Distribution Unlimited

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision unless so designated by other documentation.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
October 2017	Annual	30 Sep 2016 - 29 Sep 2017

4. TITLE AND SUBTITLE

Sensory Feedback for Lower Extremity Prostheses Incorporating Targeted Muscle Reinnervation (TMR)

5a. CONTRACT NUMBER

5b. GRANT NUMBER
W81XWH-15-1-0417

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)

Eric Rombokas, PhD

E-Mail: rombokas@uw.edu

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Seattle Institute for Biomedical and Clinical Research

1660 South Columbian Way
S-151F
Seattle WA 91808
Contact: rebecca@sibcr.org

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

We seek to improve stair descent for lower limb amputees by providing sensory feedback of foot placement. An increasing number of amputees are receiving a nerve transfer surgery, Targeted Reinnervation, that can have profound sensory effects. Touches at the site of the surgery can feel like they are originating from the amputated limb. This capability is an unprecedented opportunity to provide sensory feedback that is intuitive and useful, but sensory recovery after the surgery is not well understood. Therefore the two Specific Aims of this project are to (1) Systematically map and characterize the sensory capabilities of lower extremity Targeted Reinnervation (TR) sites under tactile stimulation, and (2) Measure the effects of vibrotactile cues of foot placement on stair descent of transtibial amputees. This year we have: created the first speed-adapting stair descent machine; developed new tactile stimulators that we expect to use in later stages of this project; and completed baseline studies to calibrate technologies and protocols on participants without amputation.

15. SUBJECT TERMS

Prosthetic Limb, Lower Extremity, Mobility, Locomotion, Stair, Sensory Replacement, Sensory Feedback, Vibrotactile, Haptic, Psychophysics, Targeted Reinnervation, Targeted Muscle Reinnervation, Targeted Sensory Reinnervation

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					USAMRMC
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
Unclassified	Unclassified	Unclassified	Unclassified	14	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

Table of Contents

Introduction

We seek to improve stair descent for lower limb amputees by providing sensory feedback of foot placement. An increasing number of amputees are receiving a nerve transfer surgery, Targeted Reinnervation, that can have profound sensory effects. Touches at the site of the surgery can feel like they are originating from the amputated limb. This capability is an unprecedented opportunity to provide sensory feedback that is intuitive and useful, but sensory recovery after the surgery is not well understood.

Therefore the two Specific Aims of this project are to (1) Systematically map and characterize the sensory capabilities of lower extremity Targeted Reinnervation (TR) sites under tactile stimulation, and (2) Measure the effects of vibrotactile cues of foot placement on stair descent of transtibial amputees.

In this second year we have made progress toward these aims.

Keywords

Prosthetic Limb, Lower Extremity, Mobility, Locomotion, Stair, Sensory Replacement, Sensory Feedback, Vibrotactile, Haptic, Psychophysics, Targeted Reinnervation, Targeted Muscle Reinnervation, Targeted Sensory Reinnervation

Accomplishments

What are the major goals of the project?

Specific Aim 1 is to systematically map and characterize the sensory capabilities of lower extremity Targeted Reinnervation (TR) sites under tactile stimulation. This aim is divided into two Major Tasks:

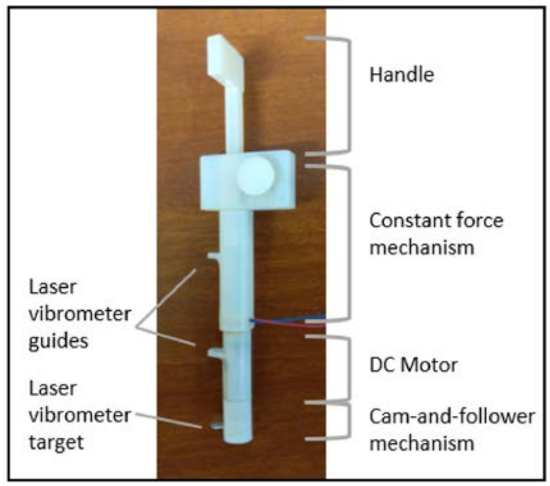


Figure 1: Tactile stimulation wand. The design allows for careful measurement and control of force and frequency.

Major Task 1: Development of Lower-Limb Vibrotactile Stimulation Technologies

We are developing devices and techniques for tactile stimulation of the residual limb for amputees who have not had TR, and the TR surgery site for those who have.

There are two main technologies under development for assessing sensory capabilities. The first (Figure 1) is a single stimulator that can precisely measure and control the force applied, as well as the frequency and linear displacement amplitude of the skin-tactor interface. The design incorporates two major elements – a constant-force sliding handle, and an effector that can be either conventional stimulators, or the cam-follower vibrotactor design pictured in Figure 2. The cam-follower design allows the frequency to be set by commands to a motor, and the amplitude to be specified by the profile of the cam. Conventional vibrotactors do not allow this free setting of both parameters, and are wider and flatter, which

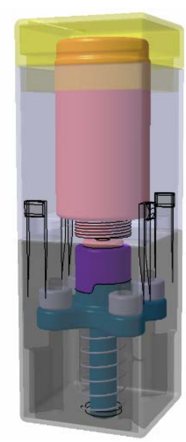


Figure 2: The cam-follower vibrotactor enables a higher-resolution tactile display than standard vibrotactors.

reduces the maximum resolution of an array of tightly placed tactors. By varying the profile of the cam and follower, a variety of waveform profiles, with distinct perceptual qualities, can be produced (Figure 4.)

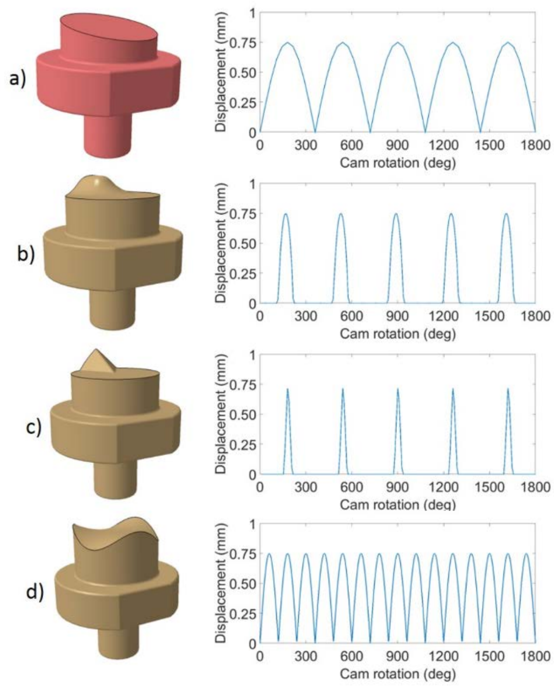


Fig. 12. Some example follower profiles and their simulated output waveforms.

Figure 4: Cam-follower profiles and the waveform that they create against the skin. Different waveforms create different perceptual feelings of stimulation.

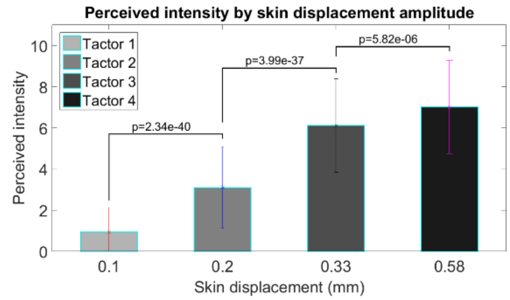


Fig. 8. Perceived touch intensity for different skin displacement amplitudes. The subjective perceived intensity increased with the skin displacement amplitude. Amplitudes are perceived different from each other(all p-values$<$0.05)

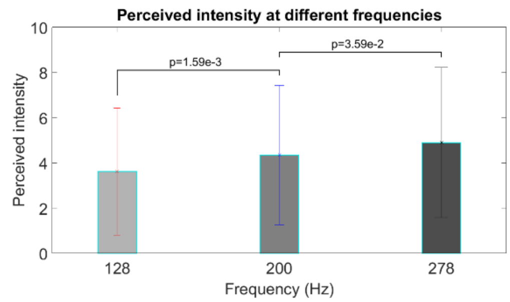


Fig. 9. Perceived touch intensity for different frequencies. The subjective perceived intensity increased with frequency. Frequencies are perceived different from each other(all p-values$<$0.05)

Figure 3: Perceived intensity of the cam-follower vibrotactor for varying frequencies and amplitude. These results are in review for publication.

Major Task 1, 2nd Technology

The second technology is an array of stimulators. This allows different places on the skin to be stimulated without manually moving the tactor, and will also be used in Specific Aim 2, when delivering the tactile feedback of foot placement. We are focusing on two prototype designs for this technology, one based on the novel cam-follower vibrotactor, and the other using piezoelectric vibrotactors (Figure 5).

Figure 5: Above: Array of piezoelectric vibrotactors, under custom skin interface enclosures. The strap affixes the array to the thigh, outside of the socket. Below: High-resolution arrays of tactors.

We have developed and pilot-tested two techniques for assessing sensory capabilities. The first is a protocol of stimulation and a touch-screen program used by the participant to indicate the felt sensations. The protocol is based on standard psychophysical experimental technique, wherein a stimulation, from either monofilaments or vibrotactors, is repeated at the same intensity for two out of three touches. The participant indicates whether and where the sensation was felt using the computer program (see Figure 6). Correct "whether" answers are used to measure minimum perceivable stimulation intensity thresholds, and "where" answers are used to map the touched locations to perceived locations. This protocol has been conducted for participants without amputation to establish baselines and guide development. The second technique makes use of Virtual Reality (VR) to provide visual and tactile touch stimulation, as depicted in Figure 7. This system provides full control over the visual experience, by changing the virtual body and virtual world. This allows us to understand how multisensory experiences of vision and taction are combined to create useful sensations. By depicting an intact limb "in virtuo" to the participants with amputation and who have had TR surgery, we are able to systematically vary stimulation parameters and collect quantitative behavioral responses.

Figure 6: Touch-screen program for indicating perceived touches.

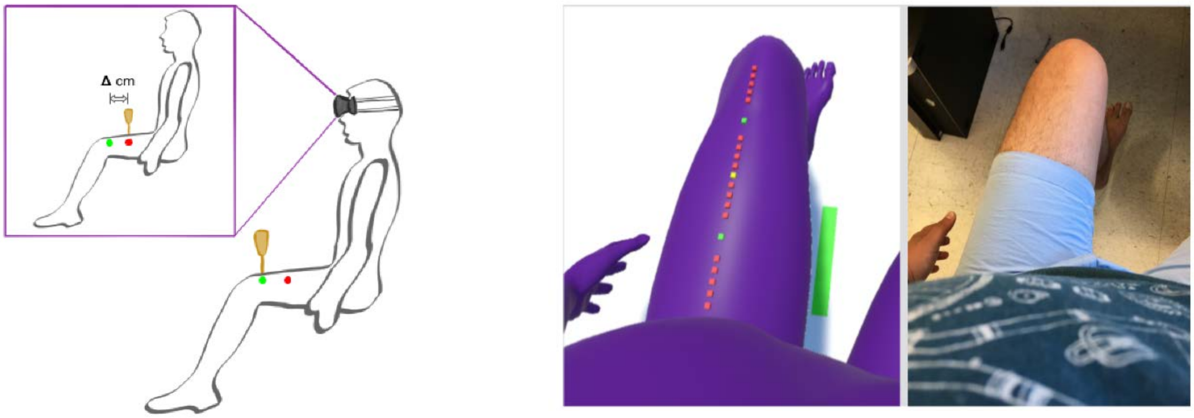


Figure 7: Visual depiction of touch in virtual reality (red dot, left) is delivered with a spatial offset from the actual location of touch (left dot, left.) The two panels on the right side of the figure depict the participants' view in VR and their real body.

Major Task 2: Mapping and characterization studies of targeted reinnervation (TR) sites
Task 2 is to perform characterization studies of the sensory capabilities of the target sites for stimulation.

Using the first sensory characterization technique, we have created a baseline from 2 control participants without amputation or nerve revision. We are now recruiting for amputees and amputees with nerve revision.

This year, we completed a study of N=12 participants using the second sensory characterization technique, the new visual-tactile two-point discrimination test described above. We have measured the degree to which participants are insensitive to spatial error between the visual and tactile sensory modalities. We deliver the stimulations to the anterior surface of the upper leg (thigh), which is anatomically our target for providing tactile sensory feedback in the sensorized prosthesis. We have found that study participants are more likely to perceive a unified visual-tactile touch even in cases of up to six centimeters of error between the modalities. We are conducting a followup in which the participants initiate the touches themselves by moving their limb, and we are have posted flyers for recruitment of amputee subjects. We anticipate these studies to inform the design of the tactile stimulation array that will display foot placement and other forces at the extremity.

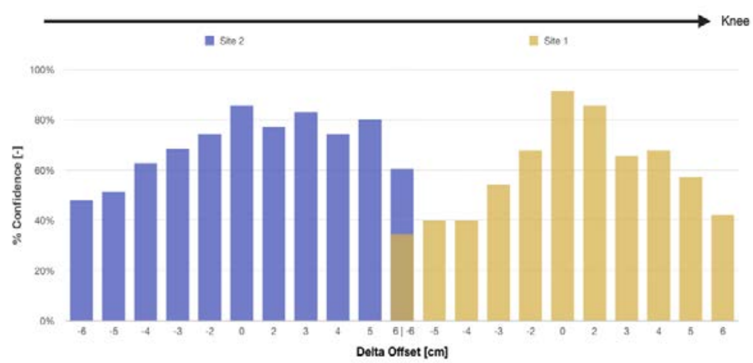


Figure 8: Confidence for offsets presented to Site 1 (closest to the knee) on the right in blue, and Site 2 to the left in yellow.

Specific Aim 2 is to determine the effects of vibrotactile cues of foot placement on stair descent of transtibial amputees. This aim consists of two Major Tasks:

Major Task 3 is the development of a speed-adapting stair descent machine. This device is based on a commercially available stair exercise product, but modified to operate in descent mode (opposite the normal direction of an exercise stairmill) and to sense the location of the user in order to adapt the speed of operation. The commercially available device normally uses electromechanical resistance via a transmission system to the steps, intended for use in stair ascent. Our design calls for replacing the alternator with a powered motor for reverse operation (Figure 7). This year we completed a pilot study using the system and have confirmed that the system adapts its speed in response to the speed of the user.

Figure 9: Stair Descent Speed-adapting Stairmill. The resistive alternator of a commercially available stairmill has been replaced with a powered motor for reverse direction operation. Motion capture during stair ambulation test using sensorized boot and vibrotactile stimulation thigh strap (right).

We are now in planning for measuring stair descent gait characteristics. These include foot placement and toe overhang, for use in the present study, but also we have determined that there is a shortage of information available about other stair descent parameters, such as self-selected speed, how it changes over time, and whether verbally-reported self-selected speed actually corresponds with the speeds users choose when they can speed up and slow down at will over the course of a few minutes.

Major Task 4: Functional study of feedback for stair descent. An initial study was conducted last year for the real-time feedback system using an insole affixed to a medical boot. This boot simulates the lack of ankle dorsiflexion and tactile sensation that contribute to difficulty in stair descent. The insole is instrumented with force sensors linearly spaced heel to toe (Figure 10). We tested two stimulation paradigms, dubbed “sensory pass-through,” in which sensor activity is rendered one-to-one from sensors to tactors, and “placement indicator” where sensor data is used to determine stair edge location and that alone is rendered to the tactors.

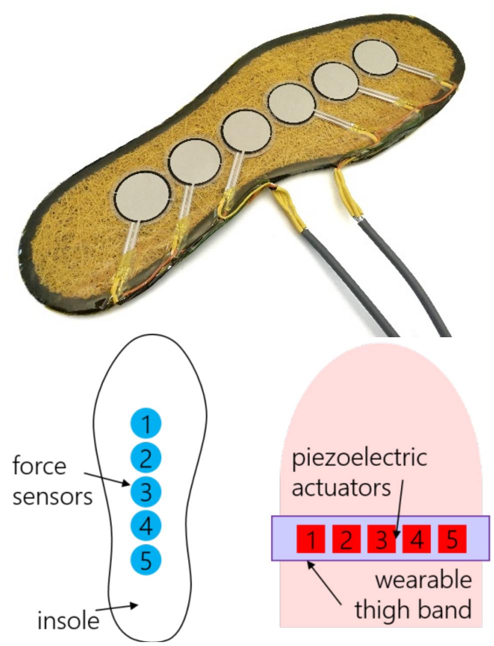


Figure 10: Foot placement sensory feedback scheme. The insole is pictured with exposed sensors but they are embedded inside the working device. The wearable tactors are pictured in Figure 5.

This year, we have demonstrated that 15 able-bodied subjects wearing the sensory replacement “medical boot” in pass-through mode show improved ability to localize their foot placement on a hidden step using the feedback system. Figure 11 depicts their ability to

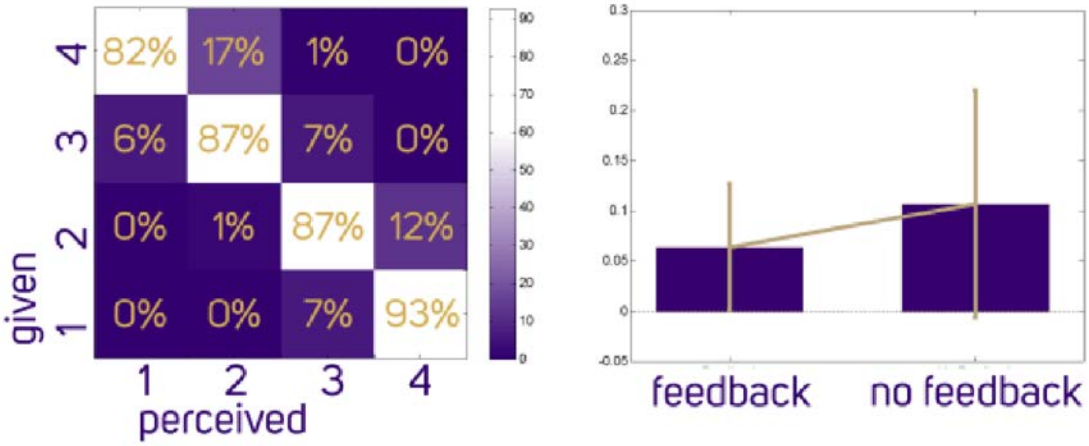


Figure 11. Confusion matrix (left) for discriminating between stimulation at each of the 4 possible sites. This demonstrates that subjects can feel the difference between different sites of stimulation. Reduced error (right) when estimating the position of the foot with respect to the edge of a hidden stair step.

discriminate among the different sensory stimuli (left), and their error in estimating the placement of their foot on a hidden stair step (right.) Details of the experimental paradigm and results can be found in "Design of a Lower Limb Prosthesis Haptic Feedback System for Stair Descent." Sie et al. *Design of Medical Devices 2017.* We have found an interesting and important detail regarding the design of our sensory insole: the conformation of the insole to the surfaces of the boot (or shoe worn over prosthesis in currently-recruiting study) is critically important. Because the plantar surface of the boot is curved, the user's weight could be borne on surfaces of the boot further back than the stair edge. These forces would then be rendered as the wrong sensory feedback cue to the user. Figure 12 demonstrates the improvement in foot placement estimation when this is taken into account. This sensor consideration is being corrected via a hardware revision of the sensorized insole system.

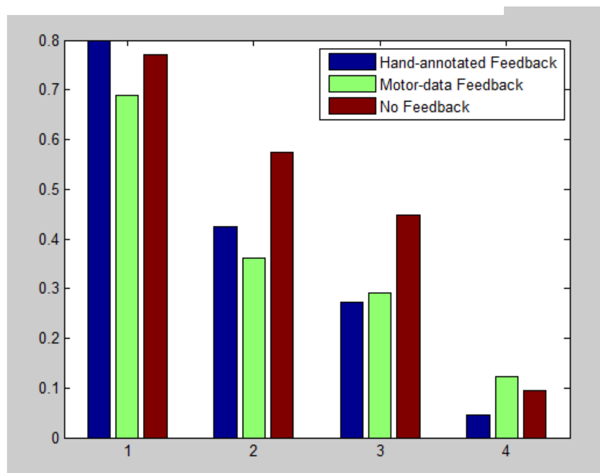


Figure 12. Foot placement was sometimes being measured incorrectly due to poor conformation of the curved plantar surface of the boot to the stair surface. User error in estimation of foot placement is reduced when accounting for this using hand-annotated placement data.

Opportunities for training and dissemination of results

The activities in this report are broad and interdisciplinary. Research assistants from Depts. Of Mechanical and Electrical engineering have spent extensive time working with the investigators to achieve these technological and methodological goals. Five presentations were given this year at the Northwest Biomechanics Symposium (NWBS) 2017, one published manuscript and four manuscripts are in preparation to disseminate the results of these efforts. We also occupied a booth for the two years of the University of Washington Engineering Discovery Days, which is an outreach event for middle school

to high school students, in which we demonstrated the prostheses, sensors, and tactors, and described the research.

Plans for next reporting period

The immediate next phase of this research is to conduct these same experiments for the amputee and Targeted Reinnervation populations. Recruitment is now open, with physician referral and flyers in place. We are currently submitting a revision to human subjects review to allow us to directly contact potential participants with Targeted Reinnervation from Harborview Medical Center, which we believe will be more effective than the current referral and passive, flyer-based recruitment.

Impact

Impact on the principal discipline of the project

Our work last year on the first “visuo tactile two-point discrimination test” led to a collaboration with Oculus Research, a virtual reality company, to further explore issues surrounding body ownership and multisensory fusion. We have created the first speed-adapting stairmill and verified its operation. We expect valuable stair ambulation data to be measured using this system. We have developed a new kind of tactile stimulator and shown that it has advantageous properties compared to currently-available tactors. We expect to include a high-resolution tactile array of these stimulators in the final stages of the Targeted Reinnervation feedback system.

Impact on other disciplines

Nothing to report.

Impact on technology transfer

Though it remains early, we anticipate that the novel tactor designs, and speed adapting stairmill, will yield eventual commercial or clinical devices.

Impact on society

Nothing to report.

Changes / Problems

Changes in approach

Nothing to report.

Problems or delays

We have recruited a new research assistant to compensate for turnover. We have also recruited a study coordinator to accommodate the increased logistical and paperwork demands associated with purchases, HR, and human subjects experiments.

Impacts on expenditures

The Total Cost budget awarded for year 2 of this project was $497,876. Expenditures from 10/1/2016 to 9/30/3017 are anticipated to be $264,988 (the September invoicing period is not closed yet). Expenditures were relatively low this year. This is the result of some graduate student turnover (December 2016) and delayed replacement later in the year (July 2017), as well as our purposeful delay in hiring a Research Specialist to coordinate the amputee trials until August 2017, when recruitment was

close to beginning. This strategy is meant to ensure funds are available throughout the recruitment period to support effort for this vitally important phase of the project. Dr. Ko's departure from the study also reduced annual expenditures this year, as did the Biostatistician not participating this year – we anticipate increased effort for this role later in the project.

Significant changes in use or care of human subjects, vertebrate animals, biohazards, or select agents

Nothing to report.

Products

Publications, conference papers, and presentations

Five presentations were given at the Northwest Biomechanics Symposium 2017, and one peer-reviewed manuscript was presented at Design of Medical Devices 2017.

Technologies or techniques

We have pioneered a variety of potentially impactful mechanical designs for tactile stimulators. We have created a speed-adapting stairmill that will yield stair ambulation data that has been previously impossible to measure, such as change in self-selected speed over time.

Participants and Other Collaborating Organizations

Name:	*Eric Rombokas*
Project Role:	*PI*
Researcher Identifier (e.g. ORCID ID):	
Nearest person month worked:	*2*
Contribution to Project:	*Oversight of all activities*
Funding Support:	*VA*
Name:	*Blake Hannaford*
Project Role:	*Co-I*
Researcher Identifier (e.g. ORCID ID):	
Nearest person month worked:	*2*
Contribution to Project:	*Oversight of development of tactile technologies and protocols*
Funding Support:	
Name:	*Janna Friedly*
Project Role:	*Co-I*
Researcher Identifier (e.g. ORCID ID):	
Nearest person month worked:	*1*
Contribution to Project:	*Consideration of amputee and TR issues in design*
Funding Support:	*UW*

Name:	*Lalit Palve*
Project Role:	*Research Assistant*
Researcher Identifier (e.g. ORCID ID):	
Nearest person month worked:	*6*
Contribution to Project:	*Stimulation protocols and tactor design*
Funding Support:	
Name:	*Huiwen Guo*
Project Role:	*Research Assistant*
Researcher Identifier (e.g. ORCID ID):	
Nearest person month worked:	*1*
Contribution to Project:	*Speed adapting stair descent machine development*
Funding Support:	
Name:	*Astrini Sie*
Project Role:	*Research Assistant*
Researcher Identifier (e.g. ORCID ID):	
Nearest person month worked:	*1*
Contribution to Project:	*Stair protocols, tactor array design, stimulation paradigms*
Funding Support:	
Name:	*David Caballero*
Project Role:	*Research Assistant*
Researcher Identifier (e.g. ORCID ID):	
Nearest person month worked:	*6*
Contribution to Project:	*VR sensory protocol and apparatus*
Funding Support:	
Name:	*Nataliya Rokhmanova*
Project Role:	*Research Assistant*
Researcher Identifier (e.g. ORCID ID):	
Nearest person month worked:	*1*
Contribution to Project:	*Sensorized insole, tactor array design, stimulation paradigms.*
Funding Support:	
Name:	*Luke Johnson*
Project Role:	*Research Assistant*
Researcher Identifier (e.g. ORCID ID):	

Nearest person month worked:	*7*
Contribution to Project:	*Engineering support, CAD and 3d printing design and fabrication*
Funding Support:	
Name:	*Jennifer Hicks*
Project Role:	*Research Coordinator*
Researcher Identifier (e.g. ORCID ID):	
Nearest person month worked:	*2*
Contribution to Project:	*IRB and HR coordination, support in team communication, logistics*
Funding Support:	
Name:	*David A. Boe*
Project Role:	*Research Specialist*
Researcher Identifier (e.g. ORCID ID):	
Nearest person month worked:	*2*
Contribution to Project:	*IRB and HR coordination, compliance with IRB / HRPO, consultation for prosthetic and amputation considerations*
Funding Support:	

Changes in the active other support of the PD/PI(s) or senior/key personnel since the last reporting period

Nothing to report.

Other organizations involved as partners

University of Washington
Seattle, WA
Collaboration, Personnel Exchanges

Harborview Medical Center
Seattle, WA
Collaboration

Special Reporting Requirements

Quad chart

See attachments

Appendices

None

Sensory Feedback for Lower Extremity Incorporating TMR

MR140172 Neuromusculoskeletal Injuries Research Award

Funding Opportunity Number: W81XWH-14-DMRDP-CRMRP-NMSIR

PI: Eric Rombokas **Org:** Seattle Institute for Biomedical and Clinical Research **Award Amount:** 1.5M

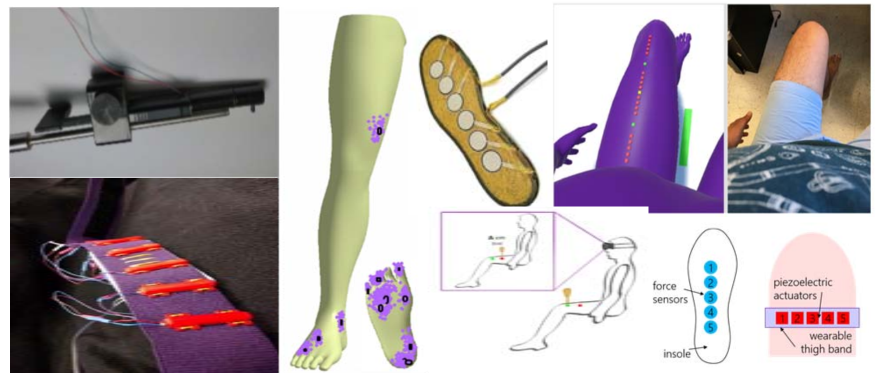
Study Aims

- **Map and characterize the sensory capabilities of lower extremity Targeted Reinnervation (TR) sites under vibrotactile stimulation.**
- **Measure the effects of vibrotactile cues of foot placement on stair descent of transtibial amputees.**

Approach

Assess sensory consequences of TR in lower extremity via Semmes-Weinstein monofilament exam, then use hand-held vibrotactile stimulator to measure for the vibrotactile haptic modality that would actually be used in an integrated sensorized prosthetic system.

Measure the effects of providing vibrotactile feedback of foot placement on self-selected speed of transtibial amputees performing stair descent. Subjects will descend integrated motion-capture speed-adaptive escalator.



Vibrotactor single stimulator (left, top) and worn array (left, bottom). Vibrotactile sensory feedback can deliver sensation of forces and foot events to the lower extremity amputee. Users having targeted reinnervation feel these sensations as if they are originating at the absent limb. Participants indicate where they felt sensations (middle). Sensory characterization is also performed by providing simultaneous visual and tactile sensation (right).

Timeline and Cost

Activities CY	16	17	18	19
Develop Vibrotactile Actuators				
Develop automatic stair machine				
Sensory mapping of TR sites				
Stair Descent with feedback				
Estimated Budget ($K)	**$496**	**$498**	**$497**	**$000**

Updated: Oct 29 2017

Goals/Milestones

- Speed-adapting stairmill user tracking complete
- Novel tactor design characterization complete
- Direct contact for Targeted Reinnervation Participants
- Sensory feedback boot hardware revision

CY18 Goals –

- Stair descent tests using speed-adapting stairmill
- Sensory Mapping / Characterization and Stair Descent
- Gait lab tests of control subjects using revised sensory boot
- Gait lab tests of stair descent for amputees without TR surgery
- Characterization of TR site sensory capabilities
- Creation of custom feedback array based on TR site